Advocacy for Multi Mobile Coil Magnetic Manipulation in Active Digestive Endoscopy.

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Abstract— **Traditional techniques of endoscopy based on flexible endoscopes are fairly reliable but poorly tolerated by patients and do not give access to the small bowel. Magnetic fields have been shown usable for manipulating endoscopic capsules, either using static coils with varying currents or mobile permanent magnets. In this short paper, we propose a novel approach which combines electromagnetic and kinematic effects and outline our research.**

I. Motivation

Conventional techniques to explore the gastrointestinal tract are based on flexible endoscopes. These techniques are fairly reliable and provide high resolution images that enable accurate diagnosis. However these procedures present several drawbacks. First, the physician needs much practice to acquire the necessary dexterity to manipulate the endoscope. Second, movements done by the endoscope inside the body are frequently painful and traumatic. Whole body anesthesia may be a solution to these pain problems but it is not always possible considering the patient's age and history. And last, these procedures do not allow observation of the whole small bowel.

In order to access small bowel and improve gastrointestinal diagnosis techniques, capsule endoscopy was initiated by Given Imaging's Pillcam [1]. However, the incapacity to control the capsule movements combined with the poor frame rate (2 to 4 images per second) does not allow for an exhaustive diagnosis of the intestine. Additionally, the capsule is subject to the irregularity of peristaltis and, therefore, the estimation of its location is approximative. Considering these drawbacks, investigation has been done to improve capsule endoscopy by replacing passive locomotion (peristaltis) by an active control of the motion.

An alternative to embedding actuation in the capsule is external actuation through magnetic fields. Two approaches can be found in the literature for magnetic manipulation, independently from the application to active digestive endoscopy. The first method is to use static coils and to control their currents to adjust the magnetic field (as in opthalmology [2], [3] or digestive endoscopy [4]). If a Helmholtz configuration is used, then the workspace is located between the two coils where one obtains uniform magnetic fields [5], [6]. This is also done in magnetic resonance imaging (MRI) systems to move a magnetic micro-object in blood vessels [7], [8]. The second method to create the appropriate external magnetic field is to use permanent magnets and to move them around the patient with a robotic system to steer the manipulated object [9], [10]. Thus, two clearly separate techniques are used to create the external magnetic field: static coils or mobile permanent magnets. This paper proposes a hybrid approach by using multiple mobile coils in order to control the motion of a magnetic capsule by both servoing the currents and moving the magnetic sources. This opens the ability to create a redundant system: one will be able to modify the magnetic field both mechanically (by moving the coils) and electrically (by adjusting the current in each coil). The aim of this redundancy is to obtain more manipulability and dexterity.

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Static coils	Mobile magnets	Mobile coils
⊕ Full dexterity	⊖ Partial dexterity	⊕ Full dexterity
⊖ Long source-to-object distance	⊖ Short source-to-object distance	⊕ Short source-to-object distance
⊖ Heat	⊕ Thermally inert	⇝ Reduced heat
⊕ On/off capacity	⊖ Always "on"	⊕ On/off capacity
⊕ Potentially stable	⊖ Intrinsic unstability	⊕ Potentially stable
⊕ Simple control	⊕ Simple control	⊕ Redundant control
⊖ Poor patient acceptability	⊖ Dangerous to the patient and staff	⇝ Light weight system

TABLE I

Some pros and cons of magnetic manipulation techniques

II. A novel approach to magnetic manipulation

The analysis of existing work (Table I) shows complementarities in the two approaches, we would like to take advantage of. Basically, the *static coils* approach has full dexterity and does global manipulation to the cost of high electrical consumption (associated to heat concerns) as the capsule evades from the sources. The latter point is troublesome in digestive endoscopy because of the human body dimensions. On the opposite, the *mobile magnets* approach does not need electrical energy to generate the field, which remains reasonable in amplitude since the magnet tracks the motion of the capsule. Nevertheless, the use of a constant field is intrinsically unstable (since the capsule is always attracted by the magnet, which can not be turned off) and offers only partial dexterity (because of the continuity of motion, the field can not be shaped arbitrarily).

Finally, both approaches suffer from operating room implementation issues. The former suffers from the same patient acceptability concerns as scanner or MRI systems, the latter from the facts that the permanent field is active in the whole room and that the robot moving the magnet is, as far as we can judge, dangerous to the patient.

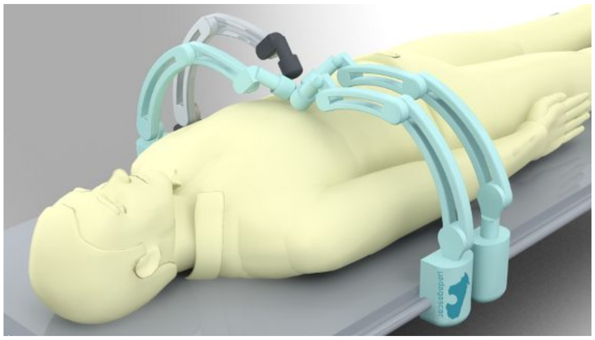

Fig. 1. Robot-assisted magnetic manipulation with several mobile coils.

Our concept, depicted in Fig. 1, consists of several coils actuated by a robotic system so they can move around the patient and stay close to the capsule. Hence, it keeps full dexterity from the use of coils while reducing the field intensity (and the energy expenditure) by a local manipulation. Moreover, the robotic system, yet to be properly designed, can be made lighter and less bulky than the existing prototypes, in order to be intrinsically safe to the patient.

III. On-going research

A. Basic electromagnetics seen from a robotics viewpoint

The two approaches actually use two different principles to adjust the magnetic forces by "shaping" the magnetic field at the capsule location. The *static coils* approach builds upon the superposition theorem: each coil is the source of a field of given shape $\mathbf{b}_i$ and the total field $\mathbf{B}$ is the linear combination of each of the individual shapes, weighted by the current I_i in each coil:

$$\mathbf{B}(\mathbf{P}) = \sum_{i=1}^{n} \mathbf{b}_i(\mathbf{P})\, I_i \tag{1}$$

where n is the number of coils used to manipulate the capsule, located in $\mathbf{P}$.

On the opposite, the *mobile magnet* approach modifies the position and orientation ${}^0[T]_m$ of the constant field ${}^m\mathbf{B}({}^m\mathbf{P})$ with respect to the global reference frame:

$${}^0\mathbf{B}({}^0\mathbf{P}) = {}^0[T]_m\ {}^m\mathbf{B}({}^0[T]_m^{-1}\ {}^0\mathbf{P}) \tag{2}$$

These two approaches can be merged into:

$${}^0\mathbf{B}({}^0\mathbf{P}) = \sum_{i=1}^{n} {}^0[T]_i\, {}^i\mathbf{b}_i({}^0[T]_i^{-1}\ {}^0\mathbf{P})\, I_i \tag{3}$$

which highlights the dependency of the magnetic field to the relative coil positions and orientations and to the current in the coils. Note that this model applies therefore to both fixed coil systems, and movable permanent magnet systems, as well as combined systems, according to the systel designer's choice to make constant or variable any of the ${}^0[T]_i$'s and I_i's terms in the expression.

B. Control strategies

Thus, this model offers us two modalities (currents and motions) to control the efforts applied to the capsule, as illustrated in Fig. 2. Since these two modalities are redundant, one still needs to define efficient control strategies.

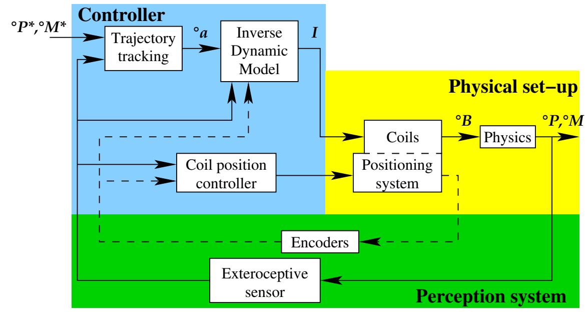

Fig. 2. A generic control scheme.

For instance, a preliminary study of ours [11] investigates a decoupling strategy where the motion of the coils is servoed from a geometric criterion, from which the currents can be controlled as in [2].

IV. Conclusions and perspectives

We believe there is plenty of space for research and development in the gap between the two existing approaches to magnetic manipulation (static coils or mobile permanent magnets). The hybrid approach we propose, based on mobile coils, should indeed allow for both technical improvements (*e.g.* reduction of thermal effects) and scientific investigation (*e.g.* in-depth analysis of dexterity in magnetic manipulation), to the service of the medical staff and for a better acceptance by the patient.

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